



Cairo University
Journal of Advanced Research



ORIGINAL ARTICLE

Predicting morphological changes DS New Naga-Hammadi Barrage for extreme Nile flood flows: A Monte Carlo analysis



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ARTICLE INFO

Article history:

Received 26 April 2012

Received in revised form 17 December 2012

Accepted 22 December 2012

Available online 14 March 2013

River Nile

Bed load

Suspended load

Monte Carlo simulation

2D numerical model

New Naga-Hammadi Barrage

ABSTRACT

While construction of the Aswan High Dam (AHD) has stopped concurrent flooding events, River Nile is still subject to low intensity flood waves resulting from controlled release of water from the dam reservoir. Analysis of flow released from New Naga-Hammadi Barrage, which is located at 3460 km downstream AHD indicated an increase in magnitude of flood released from the barrage in the past 10 years. A 2D numerical mobile bed model is utilized to investigate the possible morphological changes in the downstream of Naga-Hammadi Barrage from possible higher flood releases. Monte Carlo simulation analyses (MCS) is applied to the deterministic results of the 2D model to account for and assess the uncertainty of sediment parameters and formulations in addition to scarcity of field measurements. Results showed that the predicted volume of erosion yielded the highest uncertainty and variation from deterministic run, while navigation velocity yielded the least uncertainty. Furthermore, the error budget method is used to rank various sediment parameters for their contribution in the total prediction uncertainty. It is found that the suspended sediment contributed to output uncertainty more than other sediment parameters followed by bed load with 10% less order of magnitude.

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Introduction

The Nile drainage basin represents the longest route of sediment transport on the earth as it extends to 6671 km with more

than 1500 km in Egypt. The estimate value of total sediment load carried by the river in Egypt is in the range of 10–100 kg/s. The construction of Aswan High Dam secured Egypt with an annual supply of $55.5 \times 10^9 \text{ m}^3$ of water, controlled the maximum flow to 2900 m^3/s compared to 8100 m^3/s , and reduced the suspended sediment from 129 million tonnes/year to less than 2.27 million tonnes/year; both measured at Gaafra Station 34 km downstream Aswan (<http://en.wikipedia.org/wiki/Nile>). While building the Aswan High Dam (AHD) has stopped concurrent flooding events, River Nile is still subject to lower intensity flood waves resulting from controlled release of water from dam reservoir. This is due to increase in water

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level in Lake Nasser behind AHD and navigation requirements to increase water level in the upper delta reaches (the Delta is approximately 240 km wide and 160 km in length). Such controlled releases of flood waves are taken into consideration in design of river banks and major control structures on River Nile. However, there is insufficient data concerning the morphological changes imposed by such releases on river reaches adjacent to major control structures, such as barrages. Since water level upstream of a barrage is always maintained at a fixed level despite the flow passing, the downstream reaches are the most vulnerable to such imposed changes. Mobile bed modeling has been widely used for hydraulic and morphological assessment of real world hydraulic projects in natural rivers with high confidence. This included 2-D depth averaged models [1–10] among others. While they provide significant accuracy and CPU time saving over 3-D models, enabling simulation over significant period of prototype time and domain length, they may have limited applicability on studying mobile bed processes in river bends and around their associated training works, where secondary currents are an essential part for the process of sediment and flow interaction and hydraulics. This led to the development of various corrections for three-dimensional effects to be used in 2-D models [6,7,11]. Despite being the longest River in the world with longest route of sediment transport, River Nile has not received much amount of mobile bed hydraulic research and modeling especially in reaches at vicinity of important hydraulic structures. For instance, the morphological changes due to sediment and flow interaction in the downstream reaches of barrages are never addressed in design for new barrage despite being very important. They have shown to have profound effects on downstream bed topography, navigation, water levels and thus heading up on barrage and nearby ground water levels. While flow sediment models predict geomorphic changes in river beds, they provide no assessments of the reliability of the output. The assessment of model uncertainty is desirable to gauge the reliability and precisions in model predictions and to weigh outputs used in combination with field sample estimates [12].

One of the easiest and most efficient ways to assess model output uncertainty is the Monte Carlo technique. With the increase in computation power, the long computational time associated with this technique has diminished enabling straight forward and easy implementation. The Monte Carlo analysis was applied to assess the uncertainty of input parameters on the output decision on the rehabilitation of a sewer system based on a single computation of CSO volumes using a single storm [13]. The Monte Carlo analysis to assess the uncertainties in estimates of gully's contribution of suspended load to catchment streams [14]. Monte Carlo analysis was applied to quantify the uncertainty due to the hydraulic roughness predictor for the river bed and assess the effects on modeled water levels under design conditions [15]. To carry out the Monte Carlo analysis, the probability density function (PDF) of the input model parameters must be known. The PDF of model input parameters can be estimated by fitting experimental data, e.g. the PDF of 14 morphological parameters were estimated based on published data [16] and the PDF of 3 dam breach parameters were also estimated based on measured dam failure cases [17]. In combination with Monte Carlo simulation, the multiple linear regressions can be used to rank parameters for uncertainty. This analysis estimates the uncertainty contri-

bution of all parameters to overall output uncertainty. This method is called the error budget [12,18,19].

This paper aims to address the uncertainty associated with using a 2D mobile model in predicting the morphological changes at the downstream reach of a major barrage in Egypt; Naga-Hammadi Barrage, due to probable releases of controlled floods from AHD. This study is intended to show the important role of uncertainty analysis associated with 2D flow and sediment modeling as a tool to help control future flood releases from AHD and in design of new barrages such as new Assuit Barrage, which will be constructed 185Km downstream Naga-Hammadi Barrage.

New Naga-Hammadi Barrage

Background

There are several hydraulic structures controlling flow along the river from Aswan to Delta Barrage. These are Old Aswan Dam, Esna Barrage, Naga-Hammadi Barrage, Assiut Barrage, Delta Barrages, Zefta Barrage, and finally near to the Mediterranean; Edifna and Damitta Barrages. They divide the River Nile from Aswan to Mediterranean Sea into four reaches, between each two consecutive structures (Fig. 1a). Naga-Hammadi Barrage is considered the biggest and most important structure on River Nile located at KM359.5 in the middle of 192 km and 167 km reaches. The old Barrage has been constructed in the early 1920s 12 km north to Naga-Hammadi city in lower Egypt. The main role of this Barrage was to raise water levels in upstream reach to efficiently deliver irrigation water to more than 52,310 km² through two major canals in addition to six water lifting stations, raising water levels in the upstream to improve river navigation and decrease energy required to lift water for irrigation and potable uses.

On the year 1997, Lahmeyer International was assigned by the Egyptian Government to prepare a thorough study for upgrading the old barrage to accommodate the increase in the cultivated land by 20–30% including new reclaimed lands in addition to constructing a new 64 MW power plant to make use of the discharges passing through. The Lahmeyer study found that it wouldn't be feasible to upgrade the current barrage and recommended constructing a new barrage 3.5 km downstream the old one including a navigation lock and a power plant. The study provided detailed information on the expected hydraulic, environmental and social impacts for constructing new barrage at the selected location on the upstream side of the Barrage; however no attention has been given to the downstream reach. This is despite the fact that shortly after the construction of the old barrage, erosion was experienced in the downstream leading to lowering of water levels and thus increased heading up on the barrage and a weir has been constructed as a temporary solution to this problem [20]. Within few years, the new barrages has been constructed and put to work based on the study recommendations and with no further investigations for possible morphological changes in the downstream reach. Discharge through Naga-Hammadi Barrage is annually determined and depends on the water level behind AHD and water requirements; is maximum during summer (July–August), and minimum during winter (December–February). The average discharge in the downstream is 2170 m³/s, and 1200 m³/s during summer and winter seasons respec-

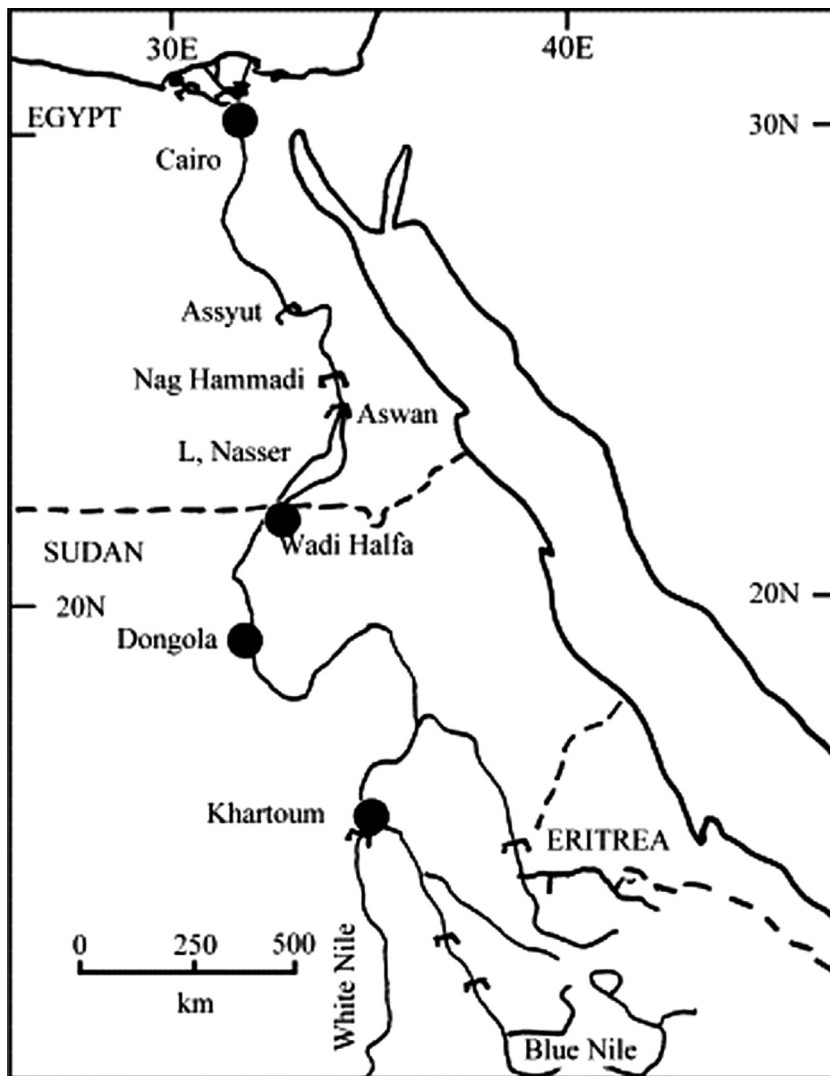


Fig. 1a River Nile.

tively. While the upstream design discharge of the barrage is $2500 \text{ m}^3/\text{s}$, the old and new barrages have been designed to have emergency openings that allow for a maximum flood discharge of $5700 \text{ m}^3/\text{s}$, which is stated by the Egyptian Ministry of Water Resources and Irrigation and an emergency flood of $7000 \text{ m}^3/\text{s}$. The Lahmeyer design report did not include a clear assessment for the morphological changes in the downstream of Naga-Hammadi Barrage for possible flood releases. Such assessment would have been important to mitigate and prevent the problems encountered in the years 1999 and 2002, which experienced the release of controlled floods of 3000 and $3700 \text{ m}^3/\text{s}$ respectively.

Study reach and available data

Downstream of Naga-Hammadi Barrage is represented in the current study by a reach of 30 km that extends from the new barrage at KM363 to KM392 after Baliana Gauge station at KM387. Preliminary runs with 1-D flow and sediment model suggested that most of the anticipated changes shall lie within this reach. This reach contains two islands in course of flow

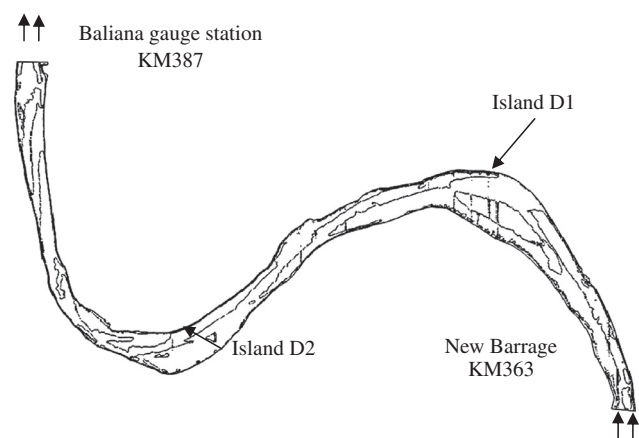


Fig. 1b Domain and topography for reach downstream of Naga-Hammadi Barrage.

inhabited by people and used mainly for cultivation and takes the S shape as shown in Fig. 1b. Initial bed topography for

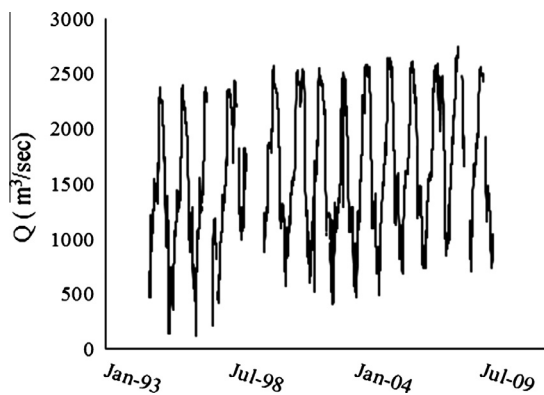


Fig. 2a Measured flow rate downstream of Naga-Hammadi Barrage.

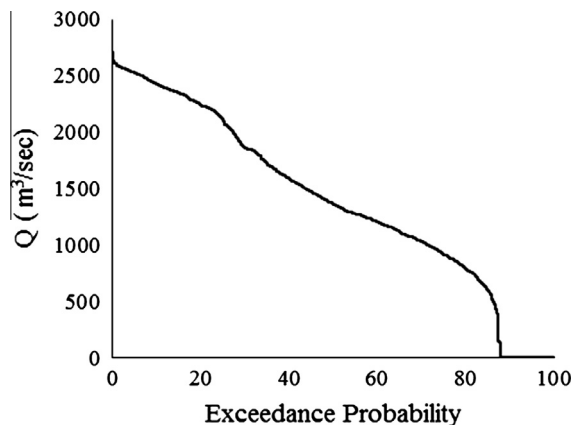


Fig. 2b Occurrence probability of current flood releases from New Naga-Hammadi Barrage.

study reach is obtained from topographic maps scale 1:5000 with contour interval 0.5 m from Nile Research Institute surveyed at 2003, 2010, and 2011 [21]. Stage hydrographs from 1995 to 2010 are available at the upstream and downstream ends of the study reach from readings of gauge stations. Fig. 2a shows that the peak flow rate has increased during the past 10 years to over 2300 m³/s, with an increase in minimum flow as well. Flows higher than 2300 m³/s, are also shown to have 17% of occurrence probability as shown in Fig. 2b. Bed soil samples are available throughout the study reach revealing a weekly non-uniform nature of river bed with mean diameters of 1.315 mm (12%), 0.415 mm (70%), and 0.1315 mm (18%) for coarse, medium and fine sand consecutively.

2-D Numerical model

CCHE2D

CCHE2D is a 2-D hydrodynamic model for unsteady turbulent open channel flow and sediment transport simulations developed at the National Center for Computational Hydroscience and Engineering (NCCHE), the University of Mississippi, School of Engineering [7]. A previous study [22] on

river sediment transport modeling found that CCHE2d model provided reliable and representative results among a number of other models. Sediment transport modeling is based on non-equilibrium bed load transport and suspended sediment transport. The model has the capability of dealing with uniform and non-uniform bed material for both bed load and suspended load transport. Bed elevation changes are accounted for and the influence of the secondary flow on the sediment motion in curved channel is also considered through incorporating empirical relations for the angle between main flow direction and that of the bed shear stress.

Model calibration

The computational grid utilized has 3000 × 200 points with an average cell size of 8 × 4 m. The curvilinear grid in *x*-*y* plane has 3000 points in the streamwise and 200 in the lateral directions. Prior to model application, the model has to be calibrated on the study reach in such a way that it produces water stage at selected gauge stations at KM363 and at KM387 compared to measured stage for measured discharge. To run stage calibration simulations; model is run in steady state under fixed bed condition utilizing standard *k*-epsilon for turbulence closure. Measured discharges are used on the upstream boundary and gauged stage on the downstream boundary. Preliminary tests were performed on the code to determine the order of magnitude of time required to reach convergence. Four groups of measured discharge data (range between 409 m³/s during the low flow season of 2003 and 2740 m³/s during the high flow season of 2008) were used as an input for the model. Through the adjustment of the bed roughness, the calculated stage is matched with historical records at the US and Baliana gauge stations. A Manning coefficient of 0.015 was found to produce best stage comparable results. It is important to note that only historical data following the year 2002 are chosen to establish initial and boundary conditions for model calibration. This is due to possible changes in the bed topography that has resulted from the large flood release at that year. It is observed from Table 1, that both measured and calculated data agree well with an average deviation of 7 cm and a maximum of 15 cm for all cases except

Table 1 Comparison of calculated and measured values of water levels (in m measured from sea surface) at Baliana gauge station (sec. 2–6) and US gauge station.

<i>Q</i> (m ³ /s)	2740		1997	
	Measured	Calculated	Measured	Calculated
Sec. 2	61.08	61.06	60.66	60.56
Sec. 4	60.95	60.89	60.50	60.48
Sec. 6	60.82	60.75	60.43	60.38
US	62.14	62.10	61.15	61.22
	1137		409	
	Measured	Calculated	Measured	Calculated
Sec. 2	59.12	59.10	57.42	56.98
Sec. 4	58.80	58.88	57.35	57.48
Sec. 6	58.62	58.55	57.27	57.18
US	59.50	59.36	58.90	58.78

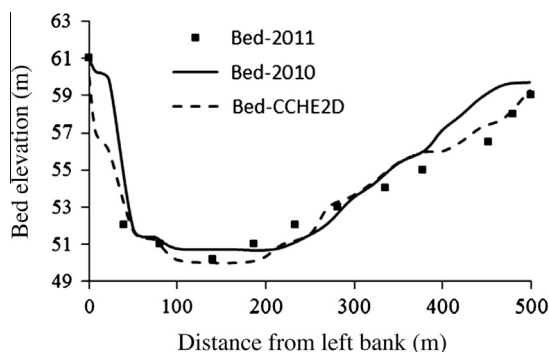


Fig. 3a Measured and predicted cross-sectional changes at KM365 showing erosion and deposition patterns.

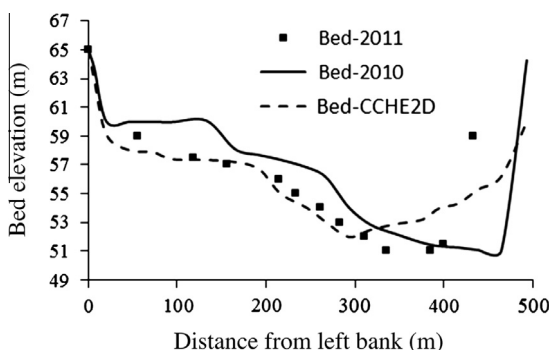


Fig. 3b Measured and predicted cross-sectional changes at KM381 showing obvious deposition.

for low flood of $409 \text{ m}^3/\text{s}$ on January 2003, where deviation reached 18 cm at US stage.

Following calibration of hydrodynamic module, the model is used to simulate the geomorphic changes in the study reach over the year 2010 utilizing measured river bed elevations on 2010 and 2011. Unsteady simulations were performed using the measured annual hydrograph during the year 2010. Sand bed material was considered non-uniform and classes were taken from collected samples in the study reach as 1.315 mm (12%), 0.415 mm (70%), and 0.1315 mm (18%) for coarse, medium and fine sand consecutively. Both suspended and bed sediment transports were considered in simulation of total load. Measured concentrations for both transport loads [21,23] along the study reach were used as the model inlet boundary. Preliminary steady-state runs were performed in an iterative procedure to reach to the best estimation for suspended sediment transport rate through matching calculation with depth averaged concentrations at Baliana station. Empirical factors in sediment equations; adaptation length for bed load and adaptation factor for suspended load are adjusted to obtain close bed topography at end of simulation (as suggested by Duan et al. [11], the adaptation length for bed load is taken as 7.3 and for suspended load as 0.04). Figs. 3a and 3b show the measured bed elevations compared to the calculated elevations for selected sections along the study reach. It is obvious that the model has reasonably reproduced changes in bed elevations, including erosion and deposition patterns over a relatively long period under various flow conditions. However, there lie a lot of uncertainties in all parts of the model.

Uncertainties in the flow model are mainly due to hydraulic roughness formulation [15] and in sediment model are due to empirical formulation of bed and total load equations and insufficient measured data on sediment loads and bed particle size. Uncertainties in flow model are considered irrelevant compared to sediment related parameter that have a direct impact on the model bed change predictions such as bed load, suspended load and bed material size. Thus, the following section presents the uncertainty analysis method that is utilized in this study followed by the application on the study reach.

Uncertainty analysis

According to Beck study [24], the overall uncertainty of any model is a combination of three sources of uncertainty: uncertainty in the input variables, uncertainty of the model parameters, and uncertainty of the model structure. It is of practice to deal only with the second source of uncertainty, which can usually be reduced by collecting more information about the parameter. This is separate from natural variability, which is a characteristic of a parameter and cannot be reduced by collecting more information. To analyze for both uncertainty and natural variability, one must use a second-order uncertainty analysis [25]. It is assumed in the current work that most parameters under investigation are only uncertain and if some are uncertain and variable, the uncertainty is assumed to dominate. Therefore, the distinction between uncertainty and variability for the CCHE2D sediment input parameters is considered irrelevant and all sediment parameters are considered as uncertain.

To assess the uncertainty in model parameter input, we shall use the Monte Carlo technique, which is a numerical technique used to calculate the output uncertainty of a model. It was developed by Stanislaw Ulam and John Von Neuman to simulate probabilistic events for military purpose in 1946 [26]. The method is robust and easy to implement; it can also handle different distribution types and always be implemented in straight-forward manner [12,27]. In the Monte Carlo technique; a probability distribution function (PDF) is needed for each model parameter and input variable that is considered to be uncertain. Initially, one random sample from the PDF of each parameter and input variable is selected and the set of samples is entered into the CCHE2D model. The model is then run as for any number of runs. The model output variables are stored and the process is repeated until a specified number of model simulations are completed. Therefore, a set of output samples is produced instead of obtaining a discrete number [25]. After a sufficiently large number of simulations, the distribution function of the output can be determined.

In the current analysis, the uncertainty in model prediction is considered due to the uncertainty in sediment parameters, such as bed load, suspended load, median bed grain size and adaptation length for bed load. Scarce measurements are found for these parameters despite of their importance in running a geomorphic simulation and predicting erosion and/or deposition patterns. To determine the PDF of these uncertain input parameters, measurements collected from previous works [21,23] are used to fit an optimum distribution. While adaptation length data are obtained from various literature sources based on expert guess and numerical recommendations. Beside the PDFs, the minimum number of simulations has to be

determined which depends on the model structure and statistics of interest. The variance of CCHE2D output bed morphological changes is set as the parameter of interest. Burmaster and Anderson [28] stated that the presence of moderate to strong correlations will have little effect on the central portion of the output distributions, but may have larger effects on the tails of the distributions. Therefore, correlations should be taken into account when there is an interest in output distribution tails in Monte Carlo analysis [27]. In the current study, no or weak correlations exist amongst sediment input variables that are considered uncertain and thus impossible parameter combinations are absent from generated random parameter contributions.

While only four parameters are considered for uncertainty analysis, it is important to determine the parameter contributing most to the output uncertainty. On drawback of Monte Carlo simulation techniques is that a combined output uncertainty can be calculated only and it is impossible to determine the contribution of each parameter to overall uncertainty of output. Therefore, it was proposed to use the least square linearization [19,29] that splits the output uncertainty into its sources and can be conducted on the results of Monte Carlo analysis. This method is a multiple regression between the parameter deviation from the mean and the output. All input uncertain sediment model parameters (D_{50} , q_b , q_{ss} and L_d) are varied at the same time in the current analysis. Using the least square linearization can help estimate the contribution of various parameters to the output uncertainty.

The least square method combination with Monte Carlo analysis has the advantages of being able to simultaneously: (1) rank parameters according to their influence in output uncertainty; (2) predict output uncertainty as a function of the uncertainty in model input variables and parameters; (3) partition error contribution of the model input variables and parameters in terms of output variance; and (4) provide the foundation for the optimal reduction of output uncertainty [30]. Moreover, sensitivity estimators such as standardized regression coefficients are easy to implement, relatively inexpensive and intuitive [31]. The least square linearization method is in essence a multiple regression between the parameter deviation from the mean and the output. If we consider a variable y , that depends on a number of independent variables; v_1, v_2, \dots, v_n . The variation of y as a function of small variations in independent variables can be expressed as:

$$\Delta y = \frac{\partial y}{\partial v_1} \Delta v_1 + \frac{\partial y}{\partial v_2} \Delta v_2 + \dots + \frac{\partial y}{\partial v_n} \Delta v_n \quad (1)$$

If y is considered as $\bar{y} + \Delta y$

$$y = \bar{y} + \frac{\partial y}{\partial v_1} \Delta v_1 + \frac{\partial y}{\partial v_2} \Delta v_2 + \dots + \frac{\partial y}{\partial v_n} \Delta v_n \quad (2)$$

The least square linearization conducted on the Monte Carlo simulation results can be expressed as follow [19].

$$\Delta v_i = v_i - m_{V_i} \approx \delta_{V_i} = v_i - V_{i,true} \quad (3)$$

where Δv_i is the difference between v_i , the random chosen sample of parameter i and m_{V_i} , the mean value of parameter i of all the random samples. The same value is assumed to be equal to δ_{V_i} , the true uncertainty of parameter i and $V_{i,true}$ is the true value of parameter i . when m Monte Carlo simulations are carried out, Δv_i for each parameter and the model output y are calculated for each simulation. Next, a multi-linear regression

on the obtained dataset is performed. The Δv_i values are considered as independent variables and the output y the dependent variable. Thus the following regression equation can be given;

$$y = w_1 \Delta v_1 + w_2 \Delta v_2 + \dots + w_n \Delta v_n + b \quad (4)$$

The regression coefficients w_i , are estimated by minimizing the sum of squared errors. Comparing this with second equation, it can be seen that these coefficients are estimates of the partial derivatives of y with respect to v_i and b is an estimate for the value of y at default parameter value.

If the uncertainties of the independent parameters are statistically independent, the overall variance of the model output can be calculated as:

$$\sigma_{\delta_y}^2 \approx \sum_{i=1}^n w_i^2 \sigma_{\delta_{v_i}}^2 \quad (5)$$

where $\sigma_{\delta_{v_i}}^2$ is the variance of the calculated difference δ_{v_i} .

Based on the regression coefficients and the variations of the parameter uncertainties, the sensitivity coefficient of each parameter i (S_{V_i}) can be approximated by [19]:

$$S_{V_i} = \frac{w_i^2 \sigma_{\delta_{v_i}}^2}{\sigma_{\delta_y}^2} \times 100\% \quad (6)$$

Depending on the scale of parameter variation, different variants of the sensitivity analysis can be conducted [32]. In the current analysis, simulations were run in which parameters are assigned probability distributions and the effect of variance in the parameters of the output distribution was assessed. This is used to rank the uncertain parameters by their contribution to the output uncertainty.

Results and discussions

Possible flood releases

The flow in River Nile through Egypt is well controlled by the Aswan High Dam since 1965 with no possible significant changes in channel morphology. In such maintained rivers, the sediment deposition is largely a function of stage and flow rate, rather than time [33]. Therefore, changes in channel morphology downstream of Naga-Hammadi shall be simulated only during high flow season (for 4 months) using selected probable controlled flood releases. Three groups of flows were chosen as 3700, 4700 and the maximum permitted by the barrage spillway 5700 m³/s, to study their morphological impacts on the study reach and on the barrage (bank is considered fixed during simulations). Measured stage rating curves were extrapolated to determine future stage values at the downstream boundary.

Morphological changes in near and far-fields

To study the erosion and deposition patterns in the study reach, it was divided into a ‘‘near-field’’ (extending downstream barrage to first Island D1) and a ‘‘far-field’’ for the rest of the reach. Under flood releases, the bed tends to erode initially – from 0.2 m to 0.7 m for $Q = 3700$ m³/s – in the near field at mid locations of sections around maximum velocity until it reaches bends where it erodes in the outside sections, and

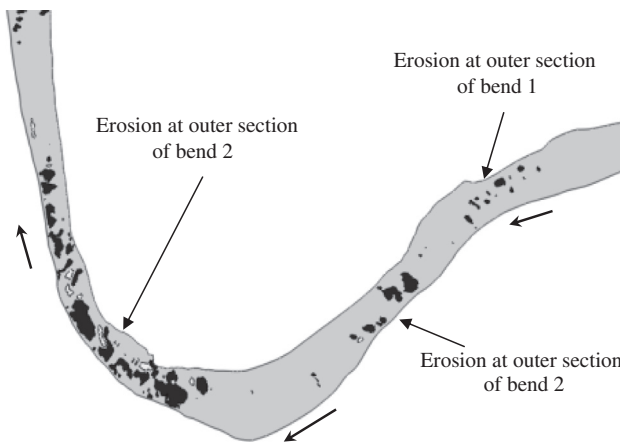


Fig. 4a Predicted erosion pattern around the second bend; $Q = 3700 \text{ m}^3/\text{s}$, $q_b = 0.01 \text{ kg/m/s}$, $q_{ss} = 0.01 \text{ kg/m/s}$, and $t = 30$ days.

continues to follow the same pattern in the far-field around the second bend. Erosion is more pronounced in the exit of the second bend (around 1.5 m for $Q = 3700 \text{ m}^3/\text{s}$) due to its angle, which is around 90° .

This erosion is analogous with the velocity distribution of flow, and accordingly bed shear stress, which tends to increase at the exit of second bend (Fig. 4a), due to decrease in river width from 550 m to less than 320 m. Simulations showed that depth averaged velocity increased from 1 m/s in the near field to 1.2 m/s in the far field and reached 1.4 m/s at second bend exit for a flow of $3700 \text{ m}^3/\text{s}$.

On the other hand, deposition in the study reach was observed in relatively smaller quantities than erosion; e.g. $97,000 \text{ m}^3$ deposition versus $106,000 \text{ m}^3$ erosion in the near field. Deposition was observed mainly at inner sides of both bends consistent with velocity behavior at bends; however higher deposition rates (deposition depth from 0.4 m to 0.9 m) were observed at the straight channel reach after exit from second bend. Both deposition and erosion rates were observed to increase more than three times during the high flow season, e.g. deposition in far field increased from $258,000 \text{ m}^3$ in June to $807,000 \text{ m}^3$ end of September (for $Q = 3700 \text{ m}^3/\text{s}$), and increase in erosion volumes is shown in Fig. 4b.

While deposition and erosion in far field have little or no impact on the barrage, the erosion in the near field has a major impact in such a way that it would decrease water depth downstream the barrage, thus increasing the heading up on the structure (heading up is defined as the difference in water levels between the upstream and the downstream of the hydraulic structure). With successive erosion cycles under normal flows, this problem occurred before and under the impact of the possible high releases, it will certainly occur again with a more pronounced impact on barrage structure condition. Fig. 4c shows the erosion pattern at the downstream of the barrage for two probable flood releases.

The heading up on Naga-Hammadi Barrage is calculated as [20]; $H_{up} = \text{upstream water depth (winter downstream water level)} - \text{average decrease in bed level downstream barrage}$). Fig. 5a shows the increase in heading up with flood releases, each measured at the end of the high flow season. Results showed that the increase in the heading up on the Naga-Ham-

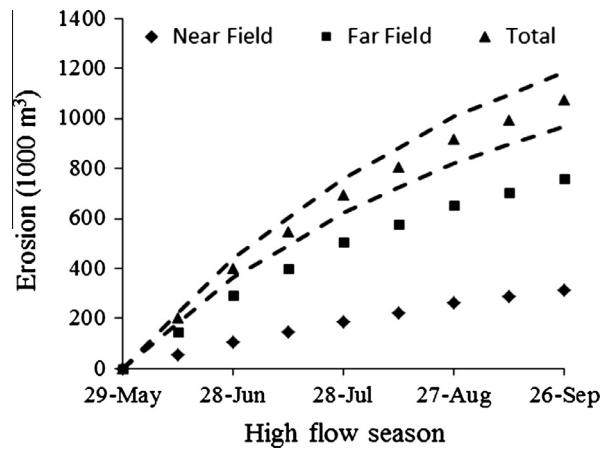


Fig. 4b Predicted erosion in the near and far fields of the barrage, $Q = 3700 \text{ m}^3/\text{s}$, $q_b = 0.01 \text{ kg/m/s}$, $q_{ss} = 0.01 \text{ kg/m/s}$; dotted line is $\pm 10\%$ of total erosion volume.

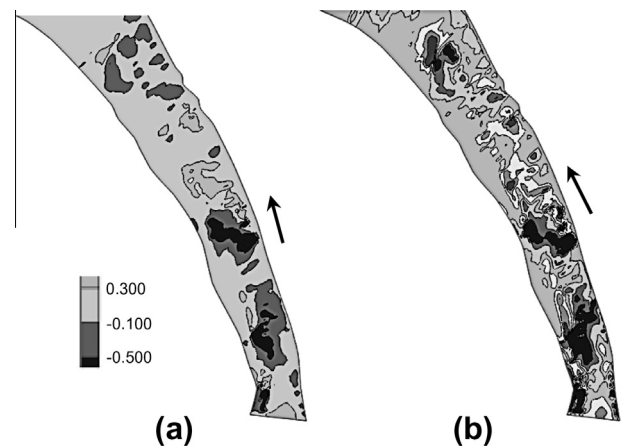


Fig. 4c Predicted erosion pattern along 4 km in the near field downstream Naga-Hammadi Barrage; (a) $Q = 3700 \text{ m}^3/\text{s}$ and (b) $Q = 4700 \text{ m}^3/\text{s}$, $q_b = 0.01 \text{ kg/m/s}$, $q_{ss} = 0.01 \text{ kg/m/s}$, and $t = 120$ days.

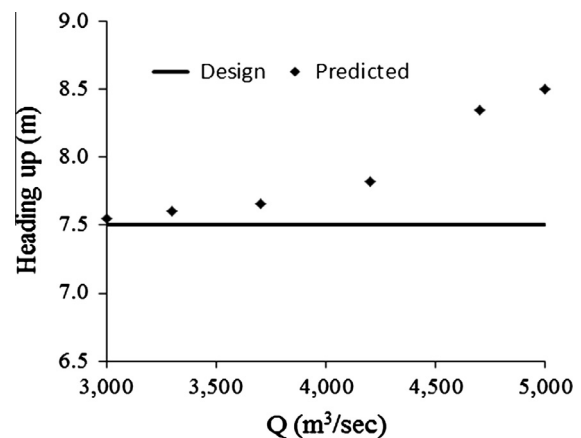


Fig. 5a Predicted increase in heading up on Naga-Hammadi Barrage as a result of downstream erosion with various flood releases.

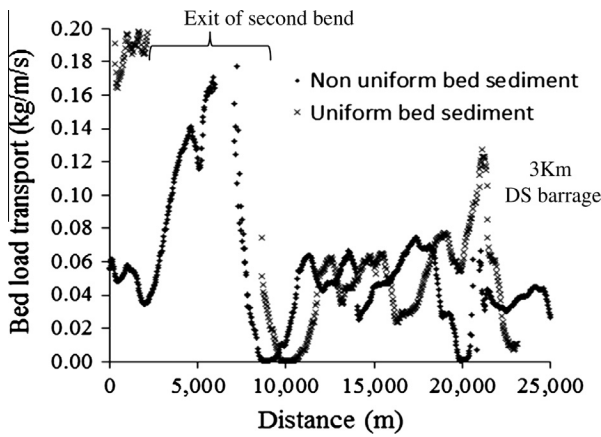


Fig. 5b Predicted bed load transport along study reach thalweg representing bed material sediment as various and single size classes, zero is at Baliana gauge station, $Q = 3700 \text{ m}^3/\text{s}$, $q_b = 0.01 \text{ kg/m/s}$, $q_{ss} = 0.01 \text{ kg/m/s}$.

madi Barrage started to be pronounced with flow of $3700 \text{ m}^3/\text{s}$ and increased significantly afterwards with increase in flood.

Initial bed material size distribution was based on recent field measurements, and thus, it reflected approximate equilibrium conditions with the initial hydrodynamics. However, based on the simulated flood releases, flow interacted with suspended sediment, bed load sediment and the original bed materials classes and modified the distribution for various bed classes to be in equilibrium with the new hydrodynamic conditions. It was observed that with all flood flows, the percentage of fine sand in bed has decreased along reach thalweg from 18% initially to 10–12% and reached 5% in locations of high erosion rates due to interaction with bed and suspended loads. On the other hand, location where deposition was observed had an increase in the amount of coarse and medium sands from 12% and 70% initially to 18% and 80% respectively, which has been delivered mainly from bed load. While it is argued that initial bed size classes are quite delicate and unforgiving when it comes to modeling erosion/deposition and especially bed load transport [34]; it is suggested that due to the slightly non-uniform nature of River Nile bed sediment, it can be grouped in one size class represented by the sediment D_{50} : 0.28 mm [23]. This approximation proved to be lacking representation of real interaction between flow and bed sediment in the study reach as shown in Fig. 5b. Since this interaction is accounted mainly to particle diameter, related flow critical parameters and the exchange between bed, bed load and suspended load along the channel, which is now crudely represented resulting in a cruder unrealistic mechanism of interaction. This is obvious in Fig. 5b at the exit of the second bend, where the absence of coarse sand bed material allowed the flow to massively erode bed sediment (erosion depth reached 5 m after 120 days for $Q = 3700 \text{ m}^3/\text{s}$) at the outside of the bend exit increasing channel depth and re-shaping velocity profile where velocity is reduced at the inner side of the bend resulting in relatively high deposition and decrease in water depth.

Navigation condition changes

As a requirement of the Nile Transportation Authority, a minimum of 2.3 m water depth is required to ensure safe navigation within all reaches of River Nile. On the other hand,

maximum velocities must not exceed 0.6 m/s during normal conditions and 0.8–1.0 m/s during high flow season. Velocities exceeding these limits will prohibit the safe navigation for a large group of river cargo ships with certain load capacity. The simulated erosion had little impact on navigation depths along the channel thalweg without violating the 2.3 m during the high flow season, while this depth was violated during low flow season to reach 1.8 m to 1.9 m at exit of second bend. Moreover, the channel thalweg has been changed significantly at second bend exit as shown in Fig. 5c due to erosion and deposition patterns at bends.

As seen from Fig. 5c, deposition in the inner side of bend has accumulated with advance in time to completely shift the navigation thalweg for more than 50 m in case of $Q = 4700 \text{ m}^3/\text{s}$, while no significant shifts were observed at the initial month of the flood, 5–20 m.

On the other hand, increase in flood flow, deposition and erosion rates triggered an increase in the depth averaged velocities close to velocities in River Nile prior to construction of AHD, thus violating the established navigation requirements

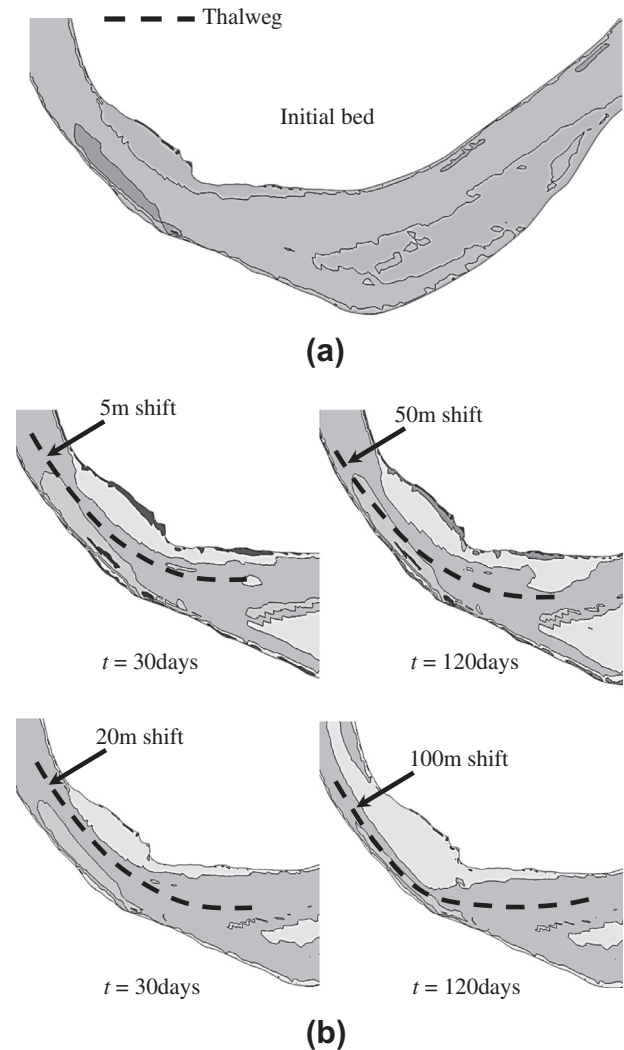


Fig. 5c Predicted change in thalweg of study reach due to erosion and deposition processes for (a) $Q = 3700 \text{ m}^3/\text{s}$, and (b) $Q = 4700 \text{ m}^3/\text{s}$ and $t = 30$ and 120 days.

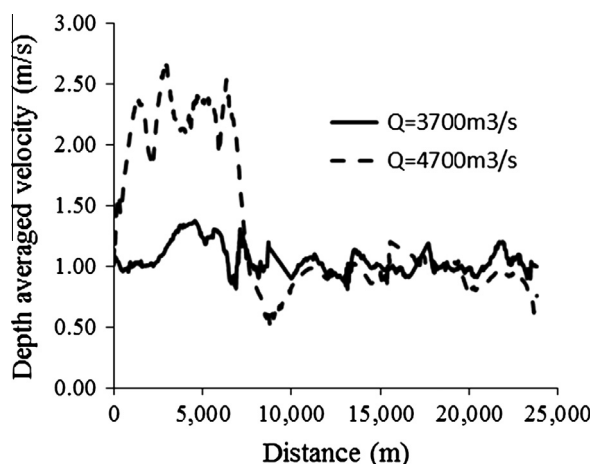


Fig. 5d Predicted depth averaged velocity along study reach thalweg for selected flood releases, $t = 120$ days.

during the high flow season. Fig. 5d presents the predicted depth averaged velocities along the channel thalweg after the

release of flood waves. In around 80% of the study reach, navigation velocity requirements are violated for both releases of $3700 \text{ m}^3/\text{s}$ and $4700 \text{ m}^3/\text{s}$. While flood flow of $3700 \text{ m}^3/\text{s}$ caused velocity of flow to increase to a maximum of 1.4 m/s , flood flow of $4700 \text{ m}^3/\text{s}$ induced a larger increase in velocity close to 1.2 m/s in 70% of the reach and 2.4 m/s in the rest of the reach after the exit from the second bend. Such velocities are not convenient to river transportation and impose safety hazards (Fig. 5d).

Monte Carlo results

The variance (which is selected to represent the output uncertainty) is found to start to converge after 2000–2500 simulations. Thus, the number of Monte Carlo simulations of 2000 is considered sufficient to predict accurately the variance of the output. This is comparable with 2050 simulations necessary to obtain good approximation for variance [12] and 2000 simulations [19].

As mentioned before, the PDFs were estimated based on fitting available measured data to various distributions. The choice of a certain distribution was based on the statistical score

Table 2 Fitting of uncertain model input parameters to PDFs and statistical scores.

Uncertain input parameter	Fitted PDF	Score in statistical tests		
		Kolmogorov Smirnov	Anderson Darling	Chi-squared
q_b	Johnson SB	0.082	0.1466	0.955
q_{ss}	Johnson SB	0.125	0.416	0.226
D_{50}	Gen. Extreme Value	0.077	0.1989	0.313
L_{ad}	Gen. Extreme Value	0.143	0.267	NA

Table 3 Ranking input sediment parameters for uncertainty in erosion in near field.

Q (m^3/s)	Parameter	Description	Contribution to overall uncertainty (%)
3700	q_b	Bed load	32.6
	q_{ss}	Suspended load	44.5
	D_{50}	Mean grain diameter	19.6
	L_{ad}	Adaptation length for bed load	3.3
4700	q_b	Bed load	20.5
	q_{ss}	Suspended load	55.9
	D_{50}	Mean grain diameter	21.6
	L_{ad}	Adaptation length for bed load	2
5700	q_b	Bed load	35.9
	q_{ss}	Suspended load	49.2
	D_{50}	Mean grain diameter	13.4
	L_{ad}	Adaptation length for bed load	1.5

Table 4 Monte Carlo simulation results.

Q (m^3/s)	Output parameter	Description	CCHE2D single run	Monte Carlo simulation	
				Mean	95%
3700	E_n	Erosion in the barrage near field (10^3 m^3)	200	400	480
	E_f	Erosion in the barrage far field (10^3 m^3)	700	630	780
	H_u	Heading up on barrage (m)	7.7	7.2	8.3
	V_n	Average navigation velocity along reach thalweg (m/s)	1.4	1.2	1.65

in tests; Kolmogorov Smirnov, Anderson Darling and Chi-squared. Normal and lognormal distributions are widely adopted PDFs for modeling uncertain parameters. But, because these distributions are unbounded on two sides, they are inappropriate for bounded parameters [35]. To exclude random variables that cannot appear in the environment, truncated distributions are useful and thus Gen. Extreme Value and Johnson SB PDF were used to represent the uncertain sediment input parameters as shown in Table 2. For each of the three chosen flood flows, the Monte Carlo analysis is performed associated with the least square linearization and the contribution of each of the chosen sediment input parameters (q_b , q_{ss} , D_{50} and adaptation length) to the output uncertainty (erosion in the near field) is shown in Table 3. It is shown that the adaptation length has the least contribution to uncertainty of results of 2D sediment model as it contributes with a maximum value of 3% in all selected flows. Other three sediment parameters are considered to be the main contributors to output uncertainty are suspended load q_{ss} , bed load q_b , and D_{50} . While their contribution to the uncertainty of the output changes depending on the flow in the reach, the suspended sediment load remains the largest contributor to uncertainty in near field erosion downstream the barrage followed by the bed load. Table 4 presents the results of Monte Carlo simulations for the flow of 3700 m³/s versus those obtained before from running the model a single run. It can be seen that the uncertainty analysis has produced mean and 95% percentile values different than those produced by the model using the chosen input parameters. The Monte Carlo simulation produced 95% percentile erosion much more than the mean produced by the same method and higher than that for the single run.

Conclusions

In this paper, the morphological changes downstream New Naga-Hammadi Barrage are studied under controlled assumed high flood releases. While only 3200 m³/s flood release has been recorded downstream the Barrage, higher flood releases of 3700 m³/s, 4700 m³/s and 5700 m³/s have been considered to test for extreme events and maximum design flows of Barrages. Deterministic runs were carried out using a 2D mobile bed numerical code to calculate the expected erosion/deposition patterns in the downstream of the New Naga-Hammadi Barrage. The model was initially calibrated based on available measurements along some of the sections in the study reaches. Predicted deposition and erosion patterns downstream the Barrage were in general agreement – at some sections – with actual changes in river bed topography as measured in 2010 and 2011. Results showed more severe erosion patterns at the far field reach of the Barrage compared to it near field, which increased during flooding months. Moreover, results showed the impact of higher flood releases on increasing the heading-up on the Barrage to more than 1.5 m above the allowable design value, which can pose some threats to its structural integrity. Moreover, the morphological changes downstream the barrage caused the navigation thalweg to shift by 20–100 m in case of 3700 m³/s and 4700 m³/s respectively over the flooding season. This was accompanied by an increase in average navigation velocity to more than 2.5 m. While, these deterministic model results could be of values for assessing morphological changes downstream the New Naga-Hammadi

Barrage, they have a considerable amount of uncertainty due to the uncertainty in empirical equations and parameters used to model suspended and bed load sediments in addition to low availability of field measurements for these parameters. Therefore, an uncertainty analysis is performed on the deterministic 2D numerical model results through Monte Carlo simulation technique to assess the reliability of predictions. Bed load, suspended load and median grain size were considered as uncertain parameters and available measurements over various reaches of River Nile are used to find the optimum fit probability distribution. It is found that the bed and suspended sediment loads distributions are best described by Johnson SB distribution, while the median grain size followed the Gen. Extreme value Distributions. The numerical model is turned into a stochastic model that samples the probability distributions randomly for each of the uncertain input variables and carries out the flow sediment calculations using the generated random parameters and then repeats this process over and over again. Simulation results have probability distributions that cover all potential outcomes of the sediment model. Comparing the stochastic with deterministic model predictions, it has been shown that variations in results could reach to one order of magnitude in case of mean erosion in the Barrage near filed for flood release of 3700 m³/s. This uncertainty in deterministic model results is a combination of the uncertainties of contributing parameters. Therefore, the error budget method is used on Monte Carlo simulation to assess the contribution of each parameter to the calculated uncertainty. As expected the uncertainty in bed load and suspended load came to be the major contribution to model output uncertainties reaching as high as 30% and 45% on average for bed and suspended load respectively. Combing the results of deterministic mobile bed modeling with the stochastic ones from MCS, a more reliable risk analysis can be conducted for probable flood releases impact on DS Naga-Hammadi Barrage. Care should be taken when applying it to other reaches with different flow and bed conditions.

Conflict of interest

The authors have declared no conflict of interest.

Acknowledgement

This work has been carried out under the financial support of Egyptian Science and Technology Development Fund (STDF), Egyptian State Ministry for Scientific Research, Project ID39.

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